

Higgs decays in supersymmetric models with light neutralinos

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ABSTRACT: In the Minimal Supersymmetric Standard Model, neutralinos lighter than 50 GeV are compatible with all accelerator, precision, and cosmological bounds. Such neutralinos might constitute a relevant decay channel for the Higgs boson, modifying its expected signatures at hadron colliders. We study the branching ratio $h \rightarrow \chi\chi$ and determine the region in the supersymmetric parameter space where it is sizable. We have found that, in fact, the Higgs may dominantly decay into neutralino pairs. Besides, as a result of this new channel, the branching ratio into visible modes, such as $h \rightarrow \gamma\gamma$, gets suppressed.

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1. Motivation

The Large Hadron Collider (LHC), now in its final stages, may soon provide evidence of new physics at the TeV scale. First of all, it should discover the Higgs boson, the only missing particle in the Standard Model. Indeed, current data from direct searches [1] and electroweak precision measurements [2] suggests a Higgs mass in the range $114 \text{ GeV} < m_h < 250 \text{ GeV}$ –well within the reach of the LHC. Once produced, the Higgs boson will instantaneously decay into lighter particles. Most analysis have assumed that its decay products are Standard Model particles: $b\bar{b}$, $\tau\tau$, $\gamma\gamma$, etc. That is not necessarily the case, however, if new physics, such as low energy supersymmetry, exists at the TeV scale.

Low energy supersymmetry is by far the best motivated scenario for physics beyond the Standard Model. The minimal supersymmetric extension of the Standard Model, known as the MSSM, solves the gauge hierarchy problem, achieves the unification of gauge couplings, explains the origin of electroweak symmetry breaking, and includes a natural dark matter candidate: the lightest neutralino.

In the MSSM the mass of the lightest neutralino is not constrained by present experiments. The often cited bound $m_{\tilde{\chi}} > 50 \text{ GeV}$ comes from the LEP limit on the chargino mass $-M_2, |\mu| > 103 \text{ GeV}$ [3]- and assumes the GUT relation among gaugino masses, which leads to $M_1 \approx 0.5M_2$ at the electroweak scale. This relation, however, does not necessarily hold, not even in models with unification of gauge couplings at high scales. And good theoretical as well as phenomenological arguments in favor of models with non-universal gaugino masses have been put forward in the literature [4]. If the GUT relation is ignored and M_1 is considered as an independent parameter, the neutralino mass can be much smaller than 50 GeV.

Accelerator constraints on light neutralinos are not strong if the neutralino is bino-like. The invisible width of the Z boson, for instance, usually constraints the existence of light particles. For a pure bino, however, the tree level coupling to the Z boson vanishes and no bounds can be derived. Indeed, according to the Review of Particle Physics [3]: “a bino of mass 0.1MeV is not excluded by collider experiments”. In a recent study, Dreiner et al

[5] concluded, along similar lines, that in the MSSM the mass of the lightest neutralino is unconstrained.

Within the standard cosmological model, light neutralinos may also explain the dark matter of the Universe [6]. In a number of papers [7], it has been shown that neutralinos with masses above 6 GeV are compatible with the observed dark matter density as well as with current bounds from direct and indirect dark matter searches. Other scenarios where light neutralinos may play a role as dark matter candidates are non-standard cosmological models, as recently pointed out by Gelmini et al [8]. They found supersymmetric models with neutralino masses as low as 1 GeV that are consistent with present bounds from accelerator and dark matter searches.

Supersymmetric models with light neutralinos, therefore, are viable and well-motivated scenarios for physics beyond the standard model. A remarkable feature of these models is the possibility that the Higgs boson decays into a neutralino pair ($h \rightarrow \chi\chi$) with a sizable branching ratio. Such invisible decay would have important implications for Higgs searches at the Tevatron and at the LHC. The detectability of a hypothetical Higgs boson that decays invisibly has been considered in several studies [9, 10, 11]. And they have all mentioned the MSSM with light neutralinos as one of its possible realizations. A detailed analysis of the process $h \rightarrow \chi\chi$ in the MSSM, however, has not been published. This paper presents such an analysis. As a first step, the supersymmetric parameters that determine the value of $\text{BR}(h \rightarrow \chi\chi)$ are identified. Next, we compare $h \rightarrow \chi\chi$ with $h \rightarrow b\bar{b}$ and show that neutralinos may indeed constitute the dominant decay mode of the Higgs boson. The behavior of $\text{BR}(h \rightarrow \chi\chi)$ is then studied as a function of M_1 , $\tan\beta$, and μ . Finally, we point out that by increasing the Higgs total decay width, the decay $h \rightarrow \chi\chi$ suppresses the Higgs branching ratio into visible channels, such as $h \rightarrow \gamma\gamma$.

2. Phenomenology

The scalar sector of the MSSM contains five physical degrees of freedom: two neutral scalar fields (h^0, H^0), one neutral pseudo scalar field (A), and two charged scalar fields (H^\pm). In the decoupling limit, when $m_A \gg m_Z$, the only light Higgs boson is h^0 and its coupling to the gauge bosons tend to those of the Standard Model Higgs boson. We will henceforth refer to h^0 as the Higgs boson and denote it simply by h . A crucial difference between the Standard Model and the MSSM is that the Higgs boson is necessarily light in the MSSM. At tree level its mass already contradicts the current bound set by LEP ($m_h > 114.4$ GeV). Higher order radiative corrections to the Higgs spectrum, however, are important and increase the theoretical prediction of m_h [12]. Yet, the Higgs mass can hardly be above 135 GeV.

The lightest neutralino of the MSSM is a linear superposition of the bino (\tilde{B}), the wino (\tilde{W}), and the two Higgsinos (H_1^0, H_2^0):

$$\chi = a_1 \tilde{B} + a_2 \tilde{W} + a_3 \tilde{H}_1^0 + a_4 \tilde{H}_2^0. \quad (2.1)$$

Due to the structure of the neutralino mass matrix, the neutralino is bino-like if $M_1 \ll M_2, \mu$, wino-like if $M_2 \ll M_1, \mu$, and higgsino-like if $\mu \ll M_1, M_2$. Since the LEP data

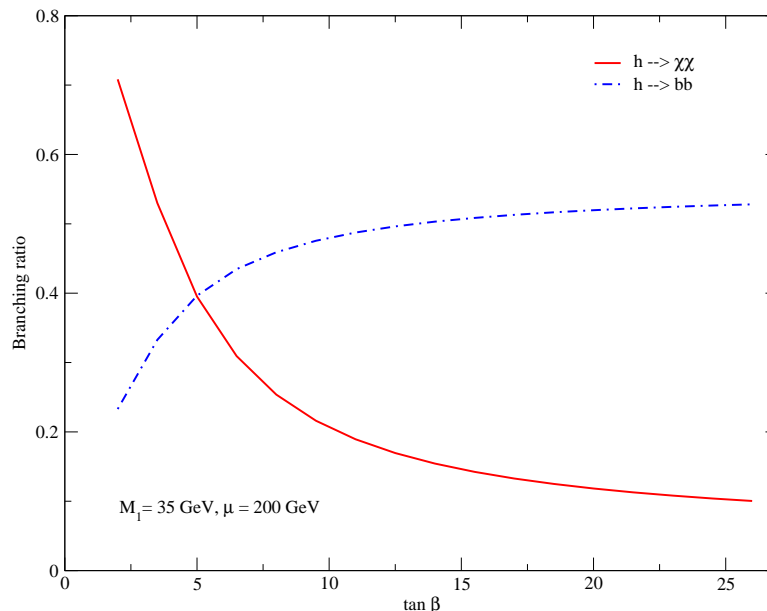


Figure 1: $\text{BR}(h \rightarrow \chi\chi)$ (solid line) and $\text{BR}(h \rightarrow bb)$ as a function of $\tan\beta$ for $\mu = 200$ GeV and $M_1 = 35$ GeV.

put a strong constraint on the chargino mass - $M_2, \mu > 103$ GeV-, light neutralinos, $m_\chi < 50$ GeV, are dominantly bino-like and have $m_\chi \sim M_1$. Small wino and higgsino components, however, are not ruled out, and they usually play an important phenomenological role. In fact, since the Higgs boson coupling to neutralinos vanishes when the neutralino is a pure gaugino or a pure higgsino [13], it is the small bino-higgsino mixing that makes the process $h \rightarrow \chi\chi$ possible at all.

A problem common to all phenomenological studies of the MSSM is the vastness of the supersymmetric parameter space. Fortunately, only few parameters are relevant for the computation of the $h \rightarrow \chi\chi$ branching ratio. We have found that $\text{BR}(h \rightarrow \chi\chi)$ is mainly determined by $\tan\beta$, μ , and M_1 . At the end, these three parameters control the all-important bino-higgsino mixture in the lightest neutralino. In addition, $M_1 \sim m_\chi$ also affects the phase space available to the decaying Higgs. For simplicity, all other parameters will be given a specific value throughout this paper. We set m_A, M_2, M_3 and all squark and slepton masses to 2 TeV; all trilinear couplings are zero except for the stop coupling which is set to 3 TeV. The effect of these parameters is not significant on $\text{BR}(h \rightarrow \chi\chi)$ but it could be important on specific accelerator or precision bounds. The Higgs mass, for instance, is rather sensitive to the value of the stop trilinear coupling. On the supersymmetric models we impose the following bounds: $m_h > 114.4$ GeV [1], $m_{\chi^\pm} > 103$ GeV [3], $-15 < (g-2)_\mu \times 10^{10} < 67$ [14], and $2.83 < \text{BR}(b \rightarrow s\gamma) \times 10^4 < 4.27$ [15]. For our calculations we use the FeynHiggs program [16] which computes, among others, the masses and mixings of the Higgs bosons in the MSSM at the two-loop level. In the next section we will study $\text{BR}(h \rightarrow \chi\chi)$ as a function of μ , $\tan\beta$, and M_1 .

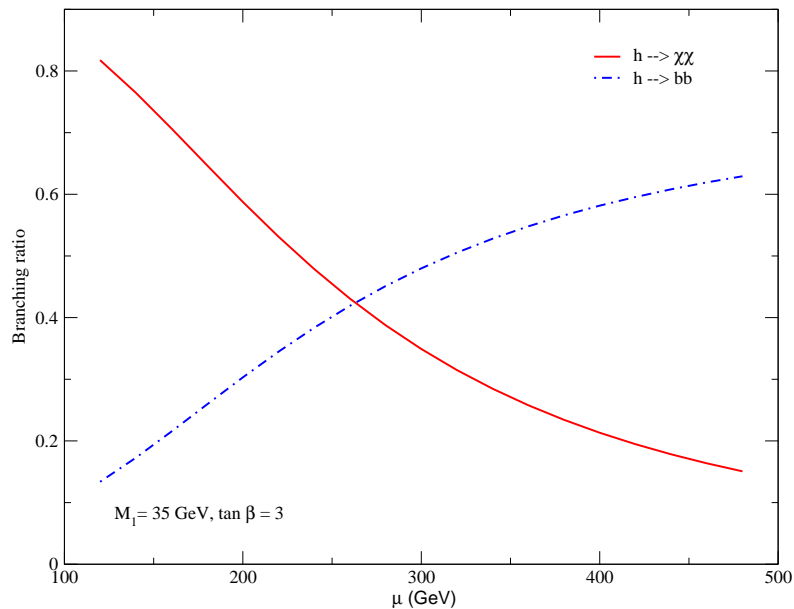


Figure 2: $\text{BR}(h \rightarrow \chi\chi)$ (solid line) and $\text{BR}(h \rightarrow bb)$ as a function of μ for $\tan\beta = 3$ and $M_1 = 35$ GeV

3. Results

Most analysis of Higgs decays in the MSSM assume that all superpartners are heavy enough to prevent the decay of the Higgs into pairs of supersymmetric particles, so that only decays into Standard Model final states are possible. In that case the dominant decay channel is bb , typically accounting for more than 80% of the decays [12]. We will see that a different picture emerges if the Higgs can decay into neutralino pairs.

Figure 1 compares the Higgs branching ratio into neutralinos with its branching ratio into b quarks as a function of $\tan\beta$ for $M_1 = 35$ GeV and $\mu = 200$ GeV. Note that these two channels account for the lion's share of the decays. $\text{BR}(h \rightarrow \chi\chi)$ is seen to decrease with $\tan\beta$ whereas $\text{BR}(h \rightarrow bb)$ increases with it. At low $\tan\beta$, the decay into neutralinos dominates, reaching $\text{BR}(h \rightarrow \chi\chi) \sim 70\%$. Around $\tan\beta = 5$ both decays give similar contributions ($\sim 40\%$) and from then on the decay into b quarks dominates. Yet, $\text{BR}(h \rightarrow \chi\chi)$ remains non-negligible ($> 10\%$) all the way up to $\tan\beta \sim 25$.

In figure 2 we compare the same two decays but now as a function of μ for $M_1 = 35$ GeV and $\tan\beta = 3$. $\text{BR}(h \rightarrow \chi\chi)$ is a decreasing function of μ whereas $\text{BR}(h \rightarrow bb)$ is an increasing one. For small values of μ , $h \rightarrow \chi\chi$ is the dominant decay mode, accounting for up to 80% of the decays. The two branching ratios become equal, $\sim 40\%$, around $\mu = 250$ GeV and from then on $h \rightarrow bb$ dominates. At $\mu = 400$ GeV, $\text{BR}(h \rightarrow \chi\chi)$ has decreased to 20% whereas $\text{BR}(h \rightarrow bb)$ has increased to about 60%.

Thus, the decay $h \rightarrow \chi\chi$ is not a small effect, it may be the dominant decay mode of the Higgs boson. As we have seen $\text{BR}(h \rightarrow \chi\chi)$ is larger when the higgsino component in the lightest neutralino is larger, that is for low $\tan\beta$ and small μ , but it remains significant within a wider range.

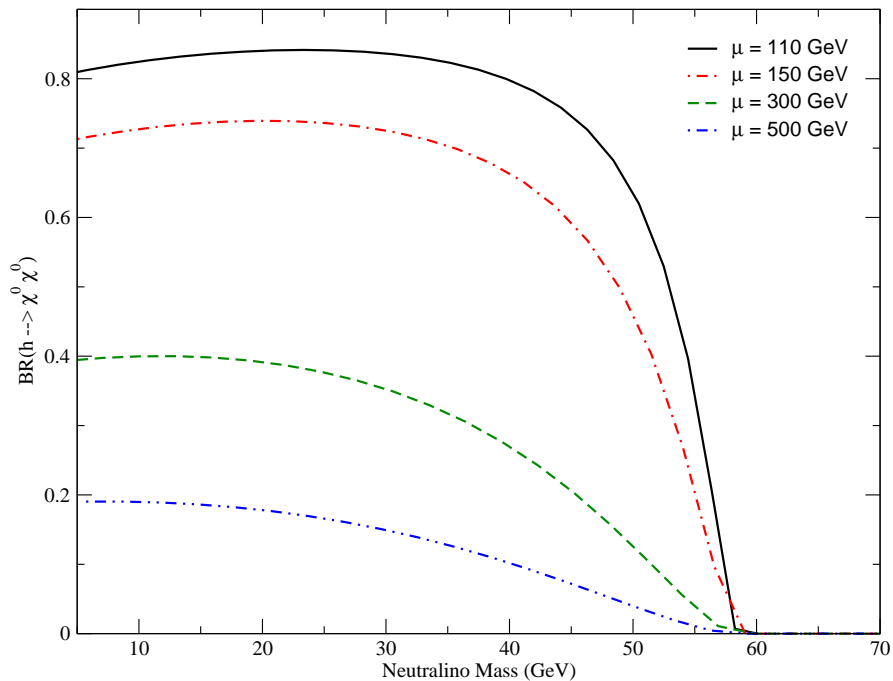


Figure 3: $\text{BR}(h \rightarrow \chi\chi)$ as a function of the neutralino mass for $\tan\beta = 3$ and different values of μ .

We proceed now to study the dependence of $\text{BR}(h \rightarrow \chi\chi)$ with the other relevant parameter, M_1 , or equivalently m_χ . Because we already know that the decay into neutralinos is important for low $\tan\beta$ and small μ we will concentrate on that region of the parameter space. Figure 3 shows $\text{BR}(h \rightarrow \chi\chi)$ as a function of the neutralino mass for $\tan\beta = 3$ and different values of μ . Due to the reduced phase space, $\text{BR}(h \rightarrow \chi\chi)$ is suppressed when the neutralino mass is close to $m_h/2$. For $m_\chi < 40$ GeV, $\text{BR}(h \rightarrow \chi\chi)$ varies mildly with m_χ . The dependence with μ , on the other hand, is very strong. At small values of μ , when the bino-higgsino mixing is larger, the branching ratio may reach 80%. For $\mu = 300$ GeV, not a small value, $\text{BR}(h \rightarrow \chi\chi)$ gets to 40% and it reaches almost 20% for $\mu = 500$ GeV.

In figure 4 we illustrate the dependence of $\text{BR}(h \rightarrow \chi\chi)$ with the neutralino mass for different values of $\tan\beta$ and $\mu = 200$ GeV. As expected, $\text{BR}(h \rightarrow \chi\chi)$ is larger for smaller values of $\tan\beta$ and it goes to zero as m_χ approaches $m_h/2$. Since the Higgs mass depends on $\tan\beta$, $\text{BR}(h \rightarrow \chi\chi)$ vanishes at slightly different neutralino masses, as observed in the figure. As before, the dependence with the neutralino mass is particularly important for neutralino masses larger than about 40 GeV. For $\tan\beta = 3$ $\text{BR}(h \rightarrow \chi\chi)$ reaches a maximum value of 60% that decreases to 10% for $\tan\beta = 25$.

Since neutralinos are stable and neutral, the process $h \rightarrow \chi\chi$ is an example of the so-called invisible decays. Generic models with an invisibly decaying Higgs boson have been considered before [9, 10, 11]. We have shown that the MSSM with light neutralinos is indeed one of its possible realizations.

Discovering a Higgs that decays invisibly would certainly be challenging, but it is within the capabilities of the LHC. The production of the Higgs in association with a Z

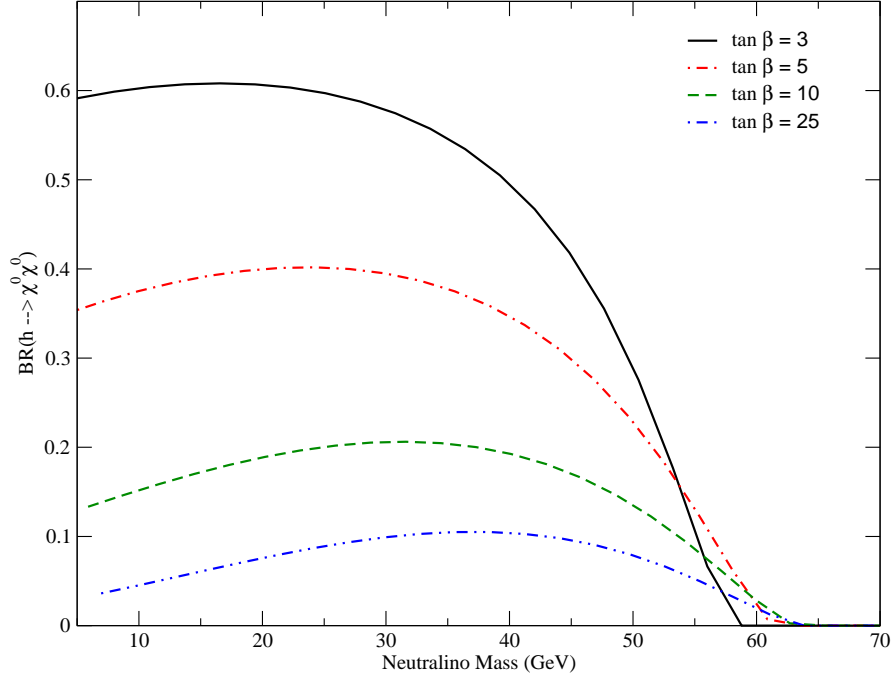


Figure 4: $\text{BR}(h \rightarrow \chi\chi)$ as a function of the neutralino mass for $\mu = 200$ GeV and several values of $\tan\beta$.

boson seems to be the most promising avenue, providing a clean signal in the dilepton plus missing energy channel. Godbole et al [10], for instance, concluded that, for $m_h = 120$ GeV and 100 fb^{-1} of integrated luminosity, invisible branching ratios larger than ~ 0.42 can be probed at 5σ . In a recent study Davoudias et al [11] considered a 100% invisibly decaying Higgs and found that the $Z + h$ channel can provide a discovery with 10 fb^{-1} for $m_h = 120$ GeV. Moreover, by combining the event rates in $Z + h$ and weak boson fusion, they noted, the Higgs boson mass could be extracted from the production cross section. Another possibility to discover a Higgs that decays into neutralino pairs is to rely on the remaining visible channels. But even them are indirectly affected by the decay $h \rightarrow \chi\chi$.

By increasing the total decay width of the Higgs, the process $h \rightarrow \chi\chi$ suppresses the branching ratio into *all* other channels, including the visible ones. If neutralinos are lighter than $m_h/2$, the Higgs branching ratios into Standard Model particles will be reduced by the factor $1 - \text{BR}(h \rightarrow \chi\chi)$ with respect to the conventional models –where neutralinos are heavier than $m_h/2$. This suppression factor is universal, it equally affects all other decay modes.

Figure 5 shows, as an example, the $\text{BR}(h \rightarrow \gamma\gamma)$ as a function of the neutralino mass for $\tan\beta = 3$ and different values of μ . As expected, for $m_\chi > m_h/2$ –when the decay $h \rightarrow \chi\chi$ is forbidden– $\text{BR}(h \rightarrow \gamma\gamma)$ is simply a constant. For $m_\chi < m_h/2$, on the other hand, the branching ratio is smaller than this constant value, with a suppression factor depending on m_χ and μ^1 . From the figure we see that the suppression factor could be more than a factor of four. If observed, such suppression would provide compelling evidence for

¹Since $\text{BR}(h \rightarrow \chi\chi)$ depends also on $\tan\beta$, the suppression will depend on $\tan\beta$ too.

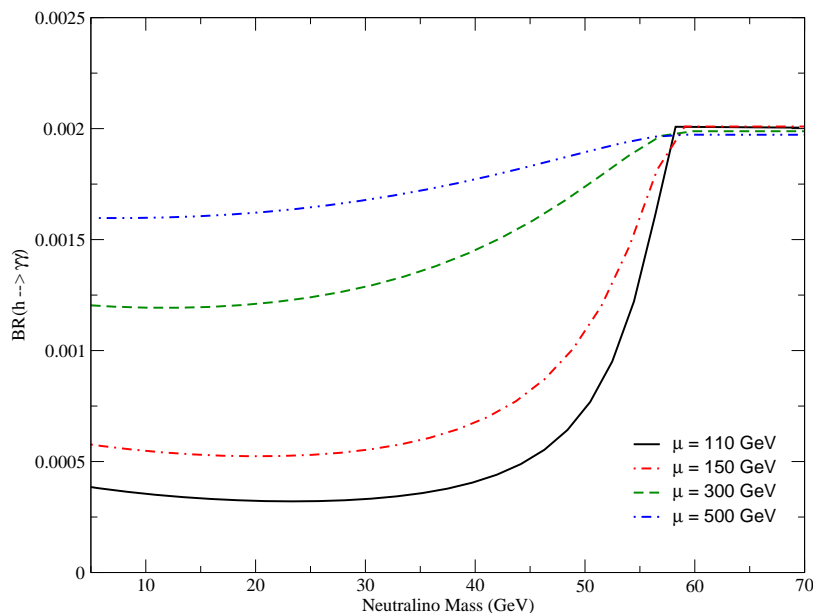


Figure 5: $\text{BR}(h \rightarrow \gamma\gamma)$ as a function of the neutralino mass for $\tan\beta = 3$ and different values of μ .

these models.

4. Conclusions

We have considered light neutralinos in the MSSM and showed that they are a relevant decay channel of the Higgs boson. The region in the supersymmetric parameter space where the Higgs decay into neutralinos is important was clearly identified: low $\tan\beta$, not so large μ , and $M_1 < 50$ GeV. After studying $\text{BR}(h \rightarrow \chi\chi)$ as a function of these three parameters, we found that it can be as large as 80%. That is, the decay $h \rightarrow \chi\chi$ might be the dominant decay mode of the Higgs boson. We also pointed out that, as a result of this additional channel, visible decay modes, such as $h \rightarrow \gamma\gamma$, are suppressed by up to a factor four.

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